The Evolution of Sihwa Dam: A Formal Design Theory Perspective

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Abstract: In this work, the evolution of Sihwa dam in Ansan, South Korea is analyzed using a combination of three formal design theories: Axiomatic Design Theory, TRIZ, and User Centered Design. The presence and influence of coupling, conflict, and compromise in the three stages of the dam are used to explain some of the problems associated with Lake Sihwa. Affordances for the three stages of the dam are also discussed and a progression of non-ideality in design is proposed.

Keywords: Water Resources Management, Sihwa Dam, Axiomatic Design Theory.

Introduction

The design and construction of water resource management systems, including tidal dams or barrages, requires careful planning, in part because of the engineering complexity associated with large civil works, and in part because they are situated within the much larger, complex coastal environment. The combined engineering and environmental complexities associated with these systems mean that failures which stem from decisions made during the design phase of the project can have an unexpected and catastrophic effect on the local habitat and population, and can result in staggering and unforeseen economic losses to the local and national economies.

This paper explores the evolution of Sihwa Dam in Ansan, South Korea in an attempt to understand the successes and failures of the project from the perspective of formal design theories and to provide guidelines for the design of similar systems in the future. Suh's (2001) Axiomatic Design (AD) Theory, Altshuller's (2005) Theory of Inventive Problem Solving (TRIZ), and Don Norman's (1988) take on human centered design are combined to provide a unique point of view on the issues associated with the project. Design matrices are constructed (1) for the system as it existed before human intervention, (2) for the first incarnation of Sihwa Dam, and (3) for the second incarnation of Sihwa Dam which will soon be completed. Coupling, conflict, and compromise within the matrices is identified and discussed. The need for including functional requirements associated with environmental protect is demonstrated. Finally, secondary and tertiary effects are examined by exploring the affordances which were added and removed with each new variation. The result is an improved understanding of the design of tidal dams and barrages which can be used to avoid repeating the mistakes of the past. It also highlights some of the similarities, differences, and shortcomings of the theories used here.

This paper is an extension of previous work by Thompson et al. (2008) and part of a larger effort to understand how formal design theories and methodologies from other engineering and design fields may be used to improve design in civil and environmental engineering.

Background

In 1994, the construction of a 12.7 km long tidal barrage was completed in Ansan, South Korea. The barrage was expected to allow the reclamation of up to 170 km^2 of land. It lowered the water level in the basin, reducing the amount of soil needed for land reclamation. And, it created a fresh water reservoir, known as Lake Sihwa, to supply agricultural and industrial water to the region. (Lee 2001; Lee 2002; and Sato and Koh 2004).

As industrial developments and the local population around Lake Sihwa grew, the pollution entering the basin also increased. As early as 1995, the removal of the tides and tidal currents combined with the pollution had caused a variety of environmental problems.

Table 1 shows the pH, dissolved oxygen (DO), chemical oxygen demand (COD), total nitrogen (TN), and total phosphate (TP) levels in Lake Sihwa in 1995, 1997, and 2000. Table 2 shows the recommended limits of the same water quality indicators by application. Level I is required to protect aquatic organisms, especially those in the

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early stages of life. Level II represents the recreational limit for swimming, boating, etc. Level III indicates the recommended levels for industrial water.

The chemical oxygen demand (COD) in Lake Sihwa increased from 2 mg/L (Sato and Koh 2004) in 1994 to 17.4 mg/L by 1997 (Lee 2001) and the total nitrogen (TN) and total phosphates (TP) in the basin were five to ten times higher than recommended. (Lee 2001).

Table 1. Water Quality Indicators in Sihwa Lake [mg/L] (Lee 2001)

	pH	DO	COD	TN	TP
1995	8.1	9.9	9.5	4.78	0.16
1997	8.9	9.6	17.4	5.11	0.34
2000	8.3	11.1	4.3	1.88	0.07

Table 2. Recommended Limits of Water Quality Indicators by Application [mg/L] (Lee 2001)

	pH	DO	COD	TN	TP
Level I	7.8 -8.3	7.5	1	0.3	0.03
Level II	6.5 - 8.5	5	2	0.6	0.05
Level III	6.5 - 8.5	2	4	1	0.09

The influx of chemicals into the basin created "grossly polluted" zones in areas where the lake was less than 6 meters in depth (Hong *et al.* 1997). It led to a "drastic elevation of chlorophyll" and "unusual blooming of phytoplankton" i.e. algae blooms. (Sato and Koh 2004). The region also experienced major changes to benthic life (Sato *et al.* 2007) and a general disruption to the local food chain.

In July 1997, the Korean Ministry of the Environment decided to use the drainage gates in the barrage to allow the tides to once again enter the basin. The ebb and flow of the tides flushed the basin of accumulated contaminants and improved many aspects of water quality. Dissolved oxygen levels rose and pH levels stabilized. COD, TN and TP levels dropped dramatically. But full water quality was not restored.

In 2001, a new design was approved which would install a series of hydroelectric generators along the center of the barrage. The second iteration of Sihwa Dam would actively use the tides to regularly flush the basin and improve water quality. It would also harness the movement of the tides to generate clean energy. However, the dam would never again be able to supply fresh water to local farms (Lee 2002) and only 110 km^2 of land was ultimately reclaimed (Lee 2001).

Methods

Three formal design theories are used to analyze the progression of the design of Sihwa dam in this work: Nam P. Suh's Axiomatic Design Theory, Genrich Altshuller's TRIZ, and Donald A. Norman's interpretation of User Centered Design.

Axiomatic Design Theory (Suh 2001)
Axiomatic Design (AD) Theory is a formal design methodology that helps designers to structure their thoughts and the design process in a systematic and rational way. This, in turn, is intended to reduce trial-and-error in the design process, increase design productivity, and improve the quality of the final result.

Design in AD is defined as the interplay between what we want to achieve and how we want to achieve it. The axiomatic design process involves decomposition within and mapping across four domains: the customer domain, the functional domain, the physical domain, and the process domain. Each step represents a decision made by the designer (mapping 'what' to 'how') and highlights the relationships between the various considerations and decisions in the system.

In this work, we will only consider two of the four domains: the functional domain and the physical domain. The functional domain lists all of the 'functions' that the design must perform in order to be considered successful. These are referred to as 'functional requirements' or FRs. The physical domain describes how those functions will be achieved through the definition of 'design parameters' or DPs.

Axiomatic Design Theory has two axioms: the Independence Axiom and the Information Axiom. In this work, we will only consider the first axiom which states that the FRs must initially be defined to be independent, and that the definition of the DPs must maintain that independence to the degree possible. This is intended to reduce coupling in the system, and thus avoid unnecessary complexity which could reduce the ability of the system to achieve its FRs.

The relationship between the contents of each domain is represented through a matrix called the design matrix. Diagonal design matrices represent ‘uncoupled’ designs, where all of the functional requirements have a one-to-one relationship with their respective design parameters. Decoupled designs are indicated by upper or lower triangular matrices and represent systems where FRs are coupled to subsequent but not preceding DPs. More fully populated design matrices represent coupled designs and are considered the least desirable.

TRIZ (Altshuller 2005)
TRIZ, also known as the Theory of Inventive Problem Solving, is an algorithmic approach to technical problem solving and idea generation. TRIZ has three main postulates upon which the theory is built. First, TRIZ states that designs tend to evolve towards more ideal states which perform more functions while consuming fewer resources. The goal

of all designers is to make their designs more ideal. Secondly, the designer is urged to seek out and eliminate contradictions, which helps to increase the ideality of the design. This is related to the reduction of coupling in AD. All conflicts in a given design are due to coupling, but not all coupling results in conflict. Finally, TRIZ says that innovative design can and should be structured systematically. The components of TRIZ used here are conflict resolution and the law of ideality.

Norman's User Center Design (Norman 1988)
User centered design (also referred to as 'human centered design') is an increasingly popular approach to design, especially within industrial and product design. Donald A. Norman has written extensively about the subject in his books where he introduced the concepts of 'affordances' and 'signifiers'. Norman defines an affordance as a quality of an object or an environment that allows an individual to perform an action. Signifiers are properties or functions of the object which indicate the presence and mode of operation of affordances to the user. Affordances are different from functional requirements in that an FR is a set goals of the system, whereas an affordance is a perceived, or actual property, of a system that determines how things could possibly be used. For example, an umbrella's function is to keep you away from the sun or rain; it affords you the opportunity to stay cool and dry. Affordances may be intentional or unintentional, and good or bad.

Prior Art

A number of case studies involving dams, lake restoration and water resource management systems have been conducted to explore the problems and standards of dam constructions, including Zhenjun *et al*. (1998), Ryding and Rast (1989), and Lankford (2008). However, we are unaware of examples which use of formal design theories for the design and analysis of tidal barrages and dams aside from our previous work in this area (Thompson *et al.* 2008).

The literature search has not revealed much information on the design and analysis of civil and environmental structures that were aided by formal design methodologies. Stiassnie and Shpitalni (2007) show that early considerations of environmental implications of a product will result in a more eco-friendly design. In the past, a life cycle assessment approach was popular for addressing the impact of the resultant design on the environment, including design for optimal materials and design for recycling (Benhabib 2003). Design for the environment has been broadly described in Billatos and Basaly (1997).

The axiomatic design literature includes examples of AD being used to address marine design problems (Jang *et al*. 2002), environmental problems (Wallace 1993), and life cycle considerations (Stiassnie and Shpitalni 2007). The AD literature especially highlights the value of AD in the evaluation of conceptual designs and the ability to complete multiple design objectives homogeneously during the design process.

Although TRIZ is rarely used for construction and other civil engineering-related projects (Delgado-Hernandez 2008), it is commonly combined with other design theories. A study by Frey *et al.* (2007) combined TRIZ, AD and Highly Optimized Tolerance principles to improve the design of a system by reducing the number of parts in the system, thereby reducing complexity. Mann talks about the compatibility issues between TRIZ and AD (Mann 1999). Kim and Cochran discussed TRIZ from the perspective of AD (Kim 2000).

User centered design has been used to design human-computer interface (Norman and Draper 1986), information services (Fidel 1994) and everyday things (Norman 1988). No case studies involving civil engineering structures could be found in the literature.

Axiomatic Analysis of Sihwa Dam

To better understand the evolution of Sihwa Dam, design matrices which represent the relationship between the functional and physical domains were constructed for three different periods of time. The first matrix analyzes the functions performed by the natural tidal environment when no human intervention is present and represents the Sihwa basin before the first dam was constructed. This matrix is referred to as the "pre-matrix." The next matrix explores the first Sihwa Dam that was completed in 1994. This is referred to as the first matrix. Two versions of this matrix are presented. The last matrix represents the second Sihwa Dam which should be completed in 2009 and is referred to as the second matrix.

Pre-Matrix
The ocean and associated tides, waves, and currents perform a wide variety of functions which help to maintain productive and stable eco-systems. In this work, we have focused on two main functions that the ocean performs in maintaining the water quality in tidal estuaries: moving materials within the bulk of the water, and moving the water itself. The motion of the water moves nutrients and contaminants towards and away from the land, diluting local concentrations and distributing them to other areas where they can be used or decomposed by aquatic organisms. Tidal currents induce vertical mixing which regulates dissolved oxygen and salinity levels among others.

These functions have been listed hierarchically on the left side of Figure 1 and represent the functional requirements of a natural tidal estuary. The corresponding design parameters are listed on the

1. Move the materials within water	x														x	x	x	1. Tides
1.1. Move materials laterally		x							o	o	o	o	o	o	x	x	x	1.1. Tides
1.1.1. Move nutrients laterally			x			x	x	x	o	o	o	o	o	o	x	x	x	1.1.1. Tides
1.1.1.1. Into land / into the bay				x	x	x	x	x	o	o	o	o	o	o	x	x	x	1.1.1.1. Incoming tides
1.1.1.2. Away from land / out of the bay				x	x	x	x	x	o	o	o	o	o	o	x	x	x	1.1.1.2. Outgoing tides
1.1.2. Move contaminants laterally			x	x	x	x			o	o	o	o	o	o	x	x	x	1.1.2. Tides
1.1.2.1. Into land / into the bay			x	x	x		x	x	o	o	o	o	o	o	x	x	x	1.1.2.1. Incoming tides
1.1.2.2. Away from land / out of the bay			x	x	x		x	x	o	o	o	o	o	o	x	x	x	1.1.2.2. Outgoing tides
1.2. Move materials vertically		x	x	x	x	x	x	x	x						x	x	x	1.2. Tides
1.2.1. Move nutrients vertically		x	x	x	x	x	x	x		x					x	x	x	1.2.1. Tidal and river currents
1.2.1.1. From the surface to the bottom		x	x	x	x	x	x	x			x		x	x	x	x	x	1.2.1.1. Downwelling
1.2.1.1.1. Circulate dissolved oxygen		x	x	x	x	x	x	x				x	x	x	x	x	x	1.2.1.1.1. Molecular and turbulent diffusion
1.2.1.2. From the bottom to the surface		x	x	x	x	x	x	x			x	x	x		x	x	x	1.2.1.2. Upwelling
1.2.1.2.1. Regulate salinity		x	x	x	x	x	x	x			x	x		x	x	x	x	1.2.1.2.1. Molecular and turbulent diffusion
2. Move the water	x	x	x	x	x	x	x	x	o	o	o	o	o	o	x			2. Tides
2.1. Cover land with water	x	x	x	x	x	x	x	x	o	o	o	o	o	o		x	x	2.1. Incoming tides
2.2. Uncover the land	x	x	x	x	x	x	x	x	o	o	o	o	o	o		x	x	2.2. Outgoing tides

Fig. 1. Design Matrix for a Natural Tidal Estuary

1. Manage water resources	x					x	o	o	1. Water management system
1.1. Obtain fresh agricultural water		x	o	o	o	o	o	o	1.1. Sinkil,Hwajeong,Ansan,Banwol,Donghwa,Samhwa streams
1.2. Store the water		o	x		o	o	o	o	1.2. Tidal barrage
1.2.1. Control the quantity of water in the basin		o		x	o	o	x	o	1.2.1. Sluices in the barrage
1.3. Send water to various destinations		o	o	o	x	o	o	o	1.3. Water transportation channels (piping system)
2. Reclaim land	x	o	o	o	o	x			2. Land reclamation system
2.1. Control the quantity of water in the basin	o	o	x	x	o		x	o	2.1. Sluices in the barrage
2.2. Increase land height	o	o	o	o	o		o	x	2.2. Land fill

Fig. 2. Design Matrix for the First Sihwa Dam

1. Manage water resources	x												x	o	o	1. Water management system
1.1. Obtain fresh agricultural water		x	o	o	o	o	o	o	o	o	o	o	o	o	o	1.1.The 6 streams entering Sihwa Basin
1.2. Store the water		o	x									o	o	o	o	1.2. Tidal barrage
1.2.1. Control the quantity of water in the basin		x		x	o	o	o	o	o	o	o	x	o	x	o	1.2.1. Sluices in the barrage
1.2.2. Control the quality of water		x		x	x							o	o	x	o	1.2.2. Water quality management system
1.2.2.1. Manage salinity levels		o		x		x			x	o	x	o	o	x	o	1.2.2.1. Tides
1.2.2.1.1. Equalize salinity in the water column		o		x			x	x	x	o	x	o	o	x	o	1.2.2.1.1. Tidal current induced mixing
1.2.2.1.2. Permit salinity to flow out of the basin		o		x			o	x	o	o	x	o	o	x	o	1.2.2.1.2. Outgoing tides
1.2.2.2. Distribute DO throughout the water column		o		x		x	x	x	x	o	x	o	o	x	o	1.2.2.2. Tidal current induced mixing
1.2.2.3 Prevent water pollution		x		o		o	o	o	o	x	o	o	o	o	o	1.2.2.3 Waste water management policy
1.2.2.4. Remove water pollution		o		x		x	o	x	o	x	x	o	o	x	o	1.2.2.4. Outgoing tides
1.3. Send water to various destinations		o	o	o	o	o	o	o	o	o	o	x	o	o	o	1.3. Water transportation channels (piping system)
2. Reclaim land	x	o	o	o	o	o	o	o	o	o	o	o	x			2. Land reclamation system
2.1. Control the quantity of water in the basin	o	x	o	x	o	o	o	o	o	o	o	x		x	o	2.1. Sluices in the barrage
2.2. Increase land height	o	o	o	o	o	o	o	o	o	o	o	o		o	x	2.2. Land fill

Fig. 3. Alternative Design Matrix for the First Sihwa Dam

1. Reclaim land	x			x	o	o	o	o	o	o	x	o	o	o	o	o	o	1. Land reclamation system
1.1. Control the quantity of water in the basin		x	o	o	o	x	x	x	o	o	o	x	x	o	x	o	x	1.1. Sluices in the barrage
1.2. Increase land height		o	x	o	o	x	x	x	o	o	o	x	x	o	x	o	x	1.2. Land fill
2. Generate usable energy	x	x	o	x							x	x	o	x	o	o	x	2. Power system
2.1. Generate energy	o	x	o		x					o	o	x	o	x	o	o	x	2.1. Hydroelectric energy system
2.1.1. Create potential energy difference	o	x	o			x			o	o	o	x	o	x	o	o	x	2.1.1. Water height management
2.1.1.1. Permit water to flow into the basin	o	x	o				x	x	o	o	o	x	x	x	x	o	x	2.1.1.1. Open sluice gates
2.1.1.2. Store the water	o	x	o				x	x	o	o	o	o	o	o	o	o	o	2.1.1.2. Tidal barrage with closed sluice gates
2.1.2. Extract as kinetic energy	o	o	o			o	o	o	x	o	o	x	o	x	o	o	x	2.1.2. Turbines
2.2. Send power to destinations	o	o	o		o	o	o	o	o	x	o	o	o	o	o	o	o	2.2. Voltage difference in transmission lines
3. Protect the environment	x	o	o	x	o	o	o	o	o	o	x							3. Environmental protection measures
3.1. Manage salinity levels	o	x	o	o	o	o	x	o	o	o		x			x	o	x	3.1. Tides
3.1.1. Equalize salinity in the water column	o	x	o	o	o	o	x	o	o	o			x	x	x	o	x	3.1.1. Tidal induced mixing (Open sluice gates)
3.1.2. Permit salinity to flow out of the basin	o	x	o	o	o	o	x	o	o	o			x	x	o	o	x	3.1.2. Outgoing tides
3.2. Ensure suficient dissolved oxygen	o	x	o	o	o	o	x	o	o	o		x	x	x	x	o	x	3.2. Tidal induced vertical mixing (Open sluice gates)
3.3. Prevent water pollution	o	o	o	o	o	o	o	o	o	o		o	o	o	o	x	o	3.3. Waste water management policy
3.4. Remove water pollution	o	x	o	o	o	o	x	o	o	o		x	x	x	x	o	x	3.4. Outgoing tides (Open sluice gates)

Fig. 4. Design Matrix for the Second Sihwa Dam

right side of Figure 1. A relationship between a given FR and DP is indicated by an 'x' in the design matrix. Coupling that leads to a decoupled or triangular design matrix is shown in light grey. This type of coupling requires that the values of the design parameters be determined in a particular order. Circular coupling is shown in red.

The pre-matrix shows that a natural tidal estuary is a fully coupled system with every functional requirement fulfilled by the tides. A rectangular design matrix is shown for clarity, but the relationships between the FRs could easily be shown with a single DP and a single column matrix.

Pre-Matrix Discussion

Axiomatic design theory considers coupled systems to be the least desirable because coupling increases the complexity of the system. This, in turn, makes it more difficult to determine acceptable values for DPs in the system, makes the system behavior more difficult to predict, and often makes the system more susceptible to destabilizing influences. However, the quality of a design is also determined by how well the functional requirements are fulfilled.

In this case, the tides do an excellent job of maintaining the water quality of tidal estuaries despite their coupled state. But the highly coupled nature of the natural system should raise an immediate concern about introducing new functions or physical elements into the system for the reasons stated above.

It is certainly debatable whether or not the discussion of coupled designs is applicable to natural systems. Design, by definition, is a human activity that results in the creation of artifacts (i.e. the artificial - opposite of the natural.) This issue is further complicated by the fact that these systems have evolved over millions of years and life has evolved around them. But the complex and coupled nature of the original system is unquestionable and can be expected strongly affect human design activities that modify the existing system.

The First Sihwa Dam

The purpose of the original Sihwa Dam was two-fold: to obtain fresh agricultural water and to reclaim land. The fresh water was obtained from the six streams that empty into Sihwa Basin: the Sinkil, Hwajeong, Ansan, Banwol, Donghwa, and Samhwa. The water was stored in the basin by using a tidal barrage to isolate the incoming freshwater from the ocean. Drainage gates were installed at the southern end of the barrage to permit excess water to leave the basin during low tide.

Land reclamation was accomplished by using land fill to increase the height of the tidal flats in the area. The average water level of the basin was also lowered to decrease the cost of the land fill and prevent flooding in the area.

The decomposed functional requirements, their associated design parameters, and the design matrix for the first Sihwa Dam are shown in Figure 2. Again, there are two instances of strong coupling in this system. This is due to the fact that both of the two main functional requirements depend on the ability to control the water level in the basin and thus depend on the barrage and the drainage gates.

Unlike the coupling found in the natural tidal system, the coupling in the first Sihwa Dam is a problem. The first functional requirement benefits from maximizing the water level in Sihwa Basin because it would permit the system to store more fresh water. The second functional requirement benefits from minimizing the water level in the basin because it would permit additional land reclamation. The coupling has led to a conflict.

The most common approach to handling conflict in design is to compromise and to attempt to find a value of water level that is acceptable for both purposes. Such was the case for the first Sihwa Dam. However, this goes against one of the fundamental principles of TRIZ which requires the designer to eliminate the contradiction (Fey and Rivin 2005). Similarly, AD urges the designer to uncouple or decouple the system instead of seeking a compromise (Deo *et al.* 2004). The elimination of conflict increases ideality, decreases complexity, and maximizes the potential for innovation.

With two design theories in agreement that the conflict in the system should be removed instead of compromised away, it is immediately clear that the original system was less than ideal. However, the situation was actually much worse than it initially seems.

The First Sihwa Dam: Another Perspective

The water quality problems in Lake Sihwa that were caused by the addition of the tidal barrage were not the result of the apparent conflict between the fresh water storage and the land reclamation. Instead, there was a second conflict in the matrix that went unnoticed by the designers: the conflict between the need to block the tides to store fresh water and the need to have the tides (or an alternative mechanism) to maintain water quality. This conflict cannot be compromised away. It represents a fundamental flaw in the original design.

Figure 3 shows a second version of the original Sihwa Dam design. In this version, the system is explicitly required to maintain water quality standards in the basin. When the additional functional requirements are added, the additional coupling and conflict is immediately visible. This is what Nakao *et al.* (2009) refer to as a “coupled but over-simplified design” where one aspect of the system “interfere[s] with an unnoticed requirement.” This type of failure was found to represent 17% of all design failures in mature Japanese industries, although environmental concerns are likely excluded from far more designs than those identified in their study.

The Second Sihwa Dam

Axiomatic design theory states that in order to remove coupling from a system, two decisions can be made: the designer can remove a function, or the design may add an additional DP. In the case of Sihwa Dam, the decision was made to remove one of the functions. The generation of fresh agriculture water was removed and replaced with a functional requirement to generate electricity. In effect, the designers redefined the problem to be one that they could solve.

The design matrix for the second Sihwa Dam is shown in Figure 4. In this system, environmental protection is an explicit FR because it was at the forefront of the designer’s thoughts. The final system is still coupled according to AD and a conflict is still present. In order to generate the maximum amount of power, a larger maximum water level is preferable. However, a lower water level is again preferable for land reclamation. Fortunately, a compromise can again be reached. This represents a less-than-ideal situation in terms of design theory, but it is a practical solution to a serious problem.

Affordances

In the previous examples, the relationships between the FRs and DPs were used to identify coupling and conflict, and to determine if a compromise could be found. However, it was shown that accurately identifying all necessary FRs can be very difficult. In addition, the positive and negative side effects of the design must also be considered. Affordances are an effective tool for helping the designer to foresee the otherwise unforeseeable and prevent problems before they happen.

Table 3 presents some of the direct and indirect affordances that were present or missing in each stage of Sihwa Dam including: habitat, fish migration, recreational activities, and the development of industry and agriculture. Many of the positive affordances which were made available by the tidal system were removed by the first dam and several negative affordances were added. For example, pollution and decomposition gases were afforded the opportunity to accumulate.

Most of the positive affordances will be reinstated and the negative affordances will be removed when the second dam is completed.

Once identified, affordances can either be treated as externalities, or can be included in the design as additional functional requirements. Thus, affordances are useful tools for both identifying 'unnoticed requirements' and for predicting the side-effects of a given design.

Coupling, Conflict, and Compromise

This paper has expanded the discussion of coupling in Axiomatic Design with the help of TRIZ and user-centered design in the context of water resource management. AD was useful in helping to explicitly state the goals of the design variants and to visualize the relationships between the various functions and their design parameters. It made identifying the coupling in the system easier. And, it was able to explain why missing functional requirements can be so problematic.

AD was not as successful in differentiating between the successfulness of the various designs. It was shown that coupling was present in all states of the Sihwa system so all variants of the Sihwa Dam (including the natural state) violated the Independence Axiom. Thus, all designs were equally problematic. However, the designs clearly were not all equally good.

TRIZ was very helpful in identifying which instances of coupling were problematic (i.e. represented conflicts) and which simply increased the complexity of the system. This is one of the many reasons that TRIZ and AD are used in combination.

Table 3. Direct and Indirect Affordances in Sihwa Basin by Dam Development Stage

	Pre-Matrix	1st Matrix	2nd Matrix
1. The Sihwa Dam and its basin directly afford:			
1.1 Fish migration	Yes	No	Yes
1.2 Habitat for aquatic coastal organisms that live in and at the base of the water column	Yes	No	Yes
1.2.1 Food for coastal food chain (including birds and humans)	Yes	No	Yes
1.3 Habitat for intertidal organisms which live in tidal mudflats or tidal wetlands	Yes	No	Yes
1.4 Swimming in the basin	Yes	No	Yes
1.4.1 Transportation for pleasure (around the basin)	Yes	No	Yes
1.4.2 Transportation for Industry (around the basin)	Yes	No	No
1.5 Opportunity for garbage and other contaminants to accumulate.	No	Yes	No
2. The Sihwa Dam and its basin indirectly afford:			
2.1 Opportunity for foul-smelling decomposition gases to be released into the atmosphere	No	Yes	No
2.1.1 Opportunity for people to come into contact with foul-smelling decomposition gases	No	Yes	No
2.2 Opportunity to develop Agriculture	No	Yes	No
2.3 Opportunity to develop Industry	No	Yes	Yes

However, both AD and TRIZ recommend against compromise. Yet, both the first and second Sihwa Dam depend on it. Perhaps this is an example of what Herbert Simon (1996) refers to as “satisficing.” It is not always possible to achieve an ideal solution, especially as the complexity of the problem increases. For many systems, especially those with large uncertainties associated with human behavior, it may be necessary to settle for a design that will satisfice.

Perhaps, instead of following the Law of Ideality in TRIZ which states that designs tend to evolve towards an ideal state over time, we need to consider the Progression of Non-Ideality (Figure 5) which describes the path of design in the opposite direction. An uncoupled design is preferable to a decoupled design, which is preferable to a coupled design according to Axiomatic Design Theory. The complexity increases at each stage while the ideality decreases. A coupled design that does not result in a conflict may still be considered an acceptable, if increasingly complex, design. A design which suffers from conflict may still be saved via compromise. Whether or not it will satisfice depends on the context. A design with conflict that cannot be saved with compromise will inevitably lead to catastrophe. In this case the design is considered unacceptable. In all cases, the designer should consider revising the design and attempting to achieve a higher level of ideality in their final product.

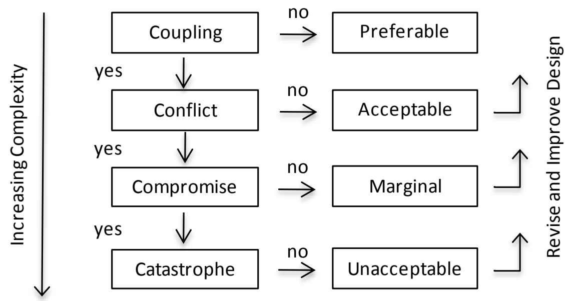

Fig. 5. Progression of Non-Ideality in Design

In the Sihwa dam case, the pre-dam ecosystem represents a good but complex ‘design’. Although there is coupling involved, there is no conflict. The first dam appears to involve coupling, conflict, and an achieved compromise – a potentially acceptable design. However, the first dam should have included water quality as a consideration. The absence of a DP to replace the tides led to a non-compromisable design – a failure in nearly every sense. The second design again involves coupling and compromisable conflict. Therefore it is again a potentially viable design based on this discussion.

Conclusions

The motivation for this work stems from the desire to understand how existing formal design theories can be used to improve design in civil and environmental engineering applications. Much of the current work in design is done in product design, industrial design, mechanical engineering, industrial engineering, and manufacturing where the focus in on the development of mass market consumer products. In contrast, civil and environmental engineering tends to produce unique, complex systems with budgets, length scales, and development and construction time scales which are orders of magnitude larger than their counterparts.

In this work, it has been shown that at least three formal design methodologies (Axiomatic Design Theory, TRIZ, and User Centered Design) can be combined to analyze the nature of the pre-existing tidal system and to explain some of the problems associated the conceptual design of the first Sihwa Dam.

It was shown that the pre-existing natural tidal system was complex and fully coupled. This makes it more difficult for designers to predict how their actions will impact the eco-system and increases the risks associated with the design. It was shown that the first Sihwa Dam had two sets of conflicts. The first could be managed through compromise. However, the second hidden risk was due to the disruption of the periodic tides that flushed the basin and could not be resolved through compromise. The system was improved by removing the second conflict and redefining the functional requirements of the second Sihwa Dam.

It was also shown that a number of affordances were affected by the problems with the first Sihwa Dam and that affordances can be used to identify hidden or latent needs and absent but necessary functional requirements.

It stands to reason that if formal design theories can identify and explain the problems with an existing design, they can also be used to avoid those problems in the future. Thus, it is our belief that formal design methodologies can be used to improve the design of civil and environmental systems. The limitations of these theories for civil and environmental systems, and adaptations and modifications needed for their use in civil and environmental engineering, will be the subject of future work.

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